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Is there a Martian atmospheric electric circuit?

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Abstract. Laboratory, analytical, and simulation studies suggest that Martian dust clouds can become significantly charged via dust/dust contact electrification. If moderate-size dust clouds on Mars are like their terrestrial counterparts, they are expected to have the capacity to create electric fields in excess of 1 kV/m. As on Earth, there is an expectation that these storm-generated electric fields terminate into both the ground and the ionosphere, coupling directly to the capacitor created by these bounding surfaces. Such charged dust storms are expected to drive ionospheric and ground currents, which complete their current path through the "fairweather" atmosphere remote from the storm. This system forms a Martian atmospheric electric circuit analogous (but not identical) to that created in the terrestrial atmosphere via thunderstorms. Here we define the requirements on Martian dust storms and the surrounding environment to create such a global electric circuit and then model the system. We find that the variation in global electric field is a strong function of Martian season, with possible values ranging in excess of hundreds of volts per meter in the active storm season (southern summer) to less than a volt per meter during the nonstorm season.

1. Introduction

On Earth a fairweather electric field develops owing to thunderstorm electric potentials that induce and drive current through the entire ionosphere and ground [*Volland*, 1984]. The individual thunderstorm electric potential acts as a battery and possesses a voltage drop of many tens of megavolts. Each storm generates about 1/2 A of current, and at any given time there are ~2000 storms active globally, driving a total of ~1000 A through the spherical capacitor system formed by the surface and ionosphere. In fairweather regions, $\sim 10^{-12}$ A/m^2 of downward directed current is present, giving rise to a ground-level fairweather electric field of ~100 V/m.

In this work we discuss the possibility that Mars possesses a similar global atmospheric electric circuit, in this case driven by dust storms. To date, there has not been a direct determination of electric forces from Martian dust devils/storms primarily because electrometry instrumentation has yet to be flown to the surface. However, there is considerable circumstantial evidence to expect such Martian saltation/suspension clouds to be electric:

1. Terrestrial dust devils are electrically active, with charged particle densities of the order of 10^6 el/cm^3. Such values are comparable to the charge particle density in the *F* region of the ionosphere. Electric fields of the order of kV/m are detected from these 100 m high structures [*Freier*, 1960; *Crozier*, 1964].
2. Laboratory studies [*Eden and Vonnegut*, 1973; *Mills*, 1977] indicate that mixing dust grains under low-pressure conditions generate $\sim 10^4$ electrons per grain. Glow and filamentary discharges are visually apparent as well.
3. Recent simulations [*Melnik and Parrot*, 1998] and analytical work [*Farrell et al.*, 1999] suggest that substantial electric fields may be possible from dust storms. *Melnik and Parrot* [1998] indicated that the convective dust devils will blow lighter negatively charged grains upward, and the charge separation with the heavy positive grains at the cloud base will generate electric fields near the atmospheric breakdown values (i.e., 20 kV/m). *Farrell et al.* [1999] presented an upper limit to dust storm charge capacity: A structure of ~5 km size can contain no more than ~200 el/cm^3. Larger charged particle densities will initiate a coronal breakdown and the development of return currents that neutralizes the excess charge.

Dust storms become electrically active owing to triboelectricity (i.e., contact/frictional electrification) [*Eden and Vonnegut*, 1973; *Melnik and Parrot*, 1998]. As grains mix, they collide with each other and the surface and become charged [*Jayaratne*, 1991]. Laboratory tests reveal that contact charging can electrify a grain to 1 femtocoulomb (fC) [*Eden and Vonnegut*, 1973] with lighter grains typically becoming negatively (−) charged and heavier grains becoming more positively (+) charged [*Ette*, 1971]. Since Martian dust storms are convective [*Gierasch*, 1974], vertical winds in the system's interior will separate and stratify the grains according to mass, with light (−) grains blown upward to the cloud tops and heavy (+) grains gravitationally descending toward the surface. The effect is to create a downward directed cloud dipole moment M. This moment is illustrated in Plate 1.

The generation of charge and charge stratification will continue until the initiation of some limiting process, such as atmospheric breakdown. As simulated [*Melnik and Parrot*, 1998], Martian cloud tribocharging is very effective and becomes so large that the internal electric fields reach breakdown levels of 20 kV/m. In such large fields, electrons are stripped from atmospheric neutrals, thereby increasing atmospheric ionization. Also, there is the development of a "glow" discharge due to electron impact excitation of neutrals. In breakdown the atmospheric coronal current self-limits the tribocharging by adding the new atmosphere charge component of opposite polarity to that being overcreated by frictional electrification of grains.

We leave open the possibility that the Martian dust tribocharge generator is very robust, creating electric field levels

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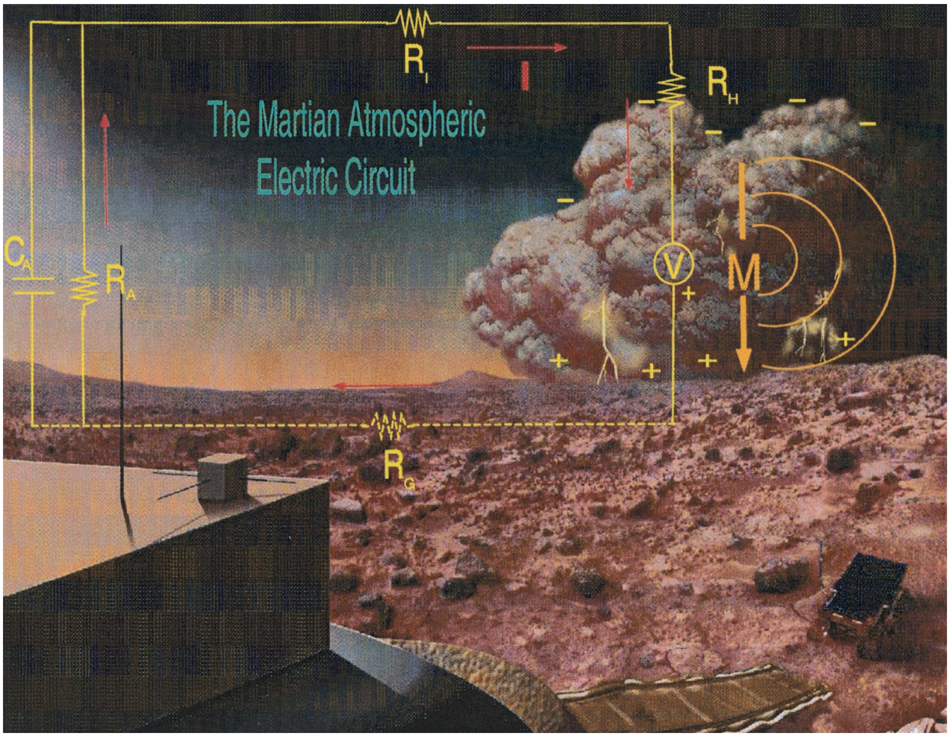

Plate 1. The Martian atmospheric electric circuit driven by triboelectrically active dust storms. Wind-blown dust creates an electric dipole moment pointed toward the ground, inducing downward current flow from the ionosphere to low altitudes. This current flow is ultimately drawn from the fairweather region which is required to "feed" the ionosphere and close the circuit.

near their breakdown limit, as simulated by *Melnik and Parrot* [1998]. The Gaussian charge limit is defined as the maximum amount of charge an object can possess above which its potential creates local ionization in the surrounding gas [*Cross*, 1987]. As a macroscopic object, the simulated dust storms of *Melnik and Parrot* [1998] were found to efficiently charge up to this Gaussian limit. The Gaussian charge limit and atmospheric breakdown were considered as the upper charging limit for the Martian dust storms modeled by *Farrell et al*. [1999]. However, charge separation processes that occur in nature are usually not as efficient. For example, terrestrial dust devils create about ± 1 mC of charge in their 100 m dipole, corresponding to an internal field of $\sim$40 kV/m. Such an electric field is $\sim$1% of terrestrial atmospheric breakdown levels. Volcanic ash charges to about 2–6% of the Gaussian limit [*Gilbert et al*., 1991], while shuttle dust experiments suggest individual grain-charging levels from 0.1 to 10% (J. Marshall, personal communication, 2000). Thus real charging processes found in nature tend not to generate to breakdown levels, but instead are only efficient enough to yield fields of a few percent of breakdown.

It should be recognized that the dust storm dipole moment is of opposite orientation to the terrestrial thunderstorm. The induction process [*Volland*, 1984] within terrestrial storms places wind-blown (+) charged light ice at cloud tops and (−) charged heavy rain/ice drops at the cloud bottom. The effect for terrestrial thunderstorms is to create a dipole moment M in the upward direction, just the opposite orientation to that shown for Mars in Plate 1.

2. Electric Circuit

Given charged dust storms within the Martian surface/ionosphere spherical capacitor, the storm-generated triboelectric fields are anticipated to induce current in the containing boundary layers in a way analogous (but not identical) to terrestrial thunderstorms in the Earth/ionosphere capacitor [*Volland*, 1984]. The current system between the ground and ionosphere is closed through the Martian atmosphere in "fairweather" regions remote from the storm. The system is an electric circuit driven by the numerous voltage sources: the dust storms.

Plate 1 illustrates the Martian atmospheric electric circuit. Each moderately sized dust storm is a voltage source V, or "battery," expected to have substantial vertical electric fields and a large overall electric potential [*Melnik and Parrot*, 1998; *Farrell et al*., 1999]. This battery drives current through the surrounding regions, including the ionosphere, atmosphere, and ground. The DC current I can be derived via

$$I = \frac{V}{(R_H + R_I + R_A + R_G)}, \tag{1}$$

where R_H is the resistance in the topside atmosphere above the storm and R_I, R_A, and R_G are the ionospheric, atmospheric, and ground resistances, respectively.

The dust storm battery draws current from regions above. The currents are induced in the ionosphere, and these flow through the resistive atmosphere above the storm, as illustrated in Plate 1. The atmospheric resistivity above the storm,

Table 1. Martian Dust Storms as Current Generators

	Regional	Moderate	Small	Devil	Earth Thunderstorm
Area (km × km)	500 × 500	50 × 50	5 × 5	0.05 × 0.05	15 × 15
Height, km	20	15	10	1	10
R_H	109 Ω	30.7 kΩ	8.7 MΩ	560 GΩ	78 MΩ
V[a]	20 MV	15 MV	10 MV	1 MV	38 MV
I,[b] A	183,000	487	1.2	2×10^{-6}	0.5
J_z,[c] A/m^2	1.3×10^{-9}	3.4×10^{-12}	8.0×10^{-15}	1.2×10^{-20}	10^{-15}
E_z,[d] V/m	451	1.2	2.8×10^{-3}	4.4×10^{-9}	1.7×10^{-2}
Storm season	1	20	100	200	2000
Nonstorm season	—	—	50	10,000	

[a]Voltage in dust cloud V is assumed 1 kV/m internal electric field multiplied by the cloud height.
[b]Current from storm with $R_H > R_{A,I,G}$: $I \sim V/R_H$.
[c]Fairweather current density, $J_z = I/A_{fair}$, where A_{fair} is the area in clear-weather regions.
[d]Ground-level fairweather electric field, $E_z = \rho_0 J_z$, where ρ_0 is the ground-level resistivity.

defined as R_H, can be estimated from recently published profiles of electron density and collision frequency [*Sukhorukov*, 1991; *Cummer and Farrell*, 1999]. As described by *Cummer and Farrell* [1999], the atmospheric pressure and temperature used in the collision frequency calculations are based on the model atmosphere of *MacElroy et al*. [1977]. The atmospheric electron density is based on a combination of model profiles [*Whitten et al*., 1971] below 80 km and experimental measurements [*Hanson et al*., 1977; *Zhang et al*., 1990] at higher altitudes. On the basis of these profiles, a zeroth-order approximation for atmospheric resistivity is $\rho(z) = \rho_0 \exp(-z/\zeta_0)$, with $\rho_0 \sim 3.57 \times 10^{11}$ Ω-m and $\zeta_0 \sim 4.8$ km. The quantity R_H is defined as the high-altitude height-integrated resistance in the column over the storm, divided by the storm cross-sectional area [*Volland*, 1982, 1984]. Given a storm of height h and base width w, R_H can be rewritten as

$$R_H = \frac{\int_h^{100\text{ km}} \rho(z)\, dz}{A_{storm}} \simeq \frac{\rho_0 \zeta_0 (e^{-h/\zeta_0})}{w^2}. \tag{2}$$

Table 1 lists the calculated values of R_H from regional, moderate, small, and devil-type dust storms. As we discuss below, as long as the ground conductivity remains above 10^{-9} S/m, R_H will be the largest resistor in the circuit (similar to the terrestrial case [*Volland*, 1982, 1984]). The current from each storm is then approximated as

$$I \sim \frac{V}{R_H}. \tag{3}$$

The high-altitude currents induced by the storm flow through the highly conductive ionospheric region. The resistance of this layer, R_I, is expected to be very small, much smaller than R_H, and thus is not a significant resistive element along the current path. The resistance in this region, when considered over the entire globe, is expected to be in the milliohm range [*Volland*, 1982, 1984].

A variable that is completely unknown is the ground conductivity R_G. VHF radar studies indicate that the surface conductivity in the first few centimeters is very low ($<10^{-8}$ S/m) [*Othoeft*, 1991]. However, the iron blend to the soil and the possible presence of trace amounts of water in the subsurface region may greatly enhance the subsurface conductivity. For the terrestrial ground the resistance in the interior is estimated to be <1 mΩ [*Volland*, 1982, 1984]. For Mars, as long as the ground conductivity σ_G remains $>10^{-9}$ S/m, the ground resistance R_G remains less than the resistance of the upper atmosphere over the storm, R_H, and the currents can be described by $I \sim V/R_H$. Tables 1 and 2 remain accurate. In essence, even for these low conductivities, the ground still possesses enough mobile charge to create ground currents from storm to fairweather regions. If $\sigma_G < 10^{-9}$ S/m, R_G exceeds R_H, and the current is approximated by $I \sim V/R_G$. The current values shown in Tables 1 and 2 are then overestimates.

The circuit is completed by upward currents flowing in fairweather regions located distant from the dust storm. These currents flow through the highly resistive atmosphere/capacitor system (R_A and C_A in Plate 1). For steady state fields the atmospheric current flow is defined by R_A, which is the total columnar resistance from ground to 100 km divided by the Martian fairweather surface area

$$R_A = \frac{\int_{0\text{ km}}^{100\text{ km}} \rho(z)\, dz}{A_{fair}} \simeq \frac{\rho_0 \zeta_0}{4\pi r^2}, \tag{4}$$

where r is the Martian planetary radius. This value for Mars is ~12 Ω, compared to 250 Ω in the more resistive terrestrial atmosphere [*Volland*, 1982, 1984].

Table 1 lists the electric fields expected at the Martian surface due to dust storms of various sizes. It is assumed that each dust storm possesses a 1 kV/m vertical electric field. The vertical electric potential drop is this field multiplied by the storm height. The internal field of 1 kV/m is ~2% of the atmospheric breakdown field. As discussed previously, simulation studies [*Melnik and Parrot*, 1998] suggest a very efficient triboelectric generation process that can create fields near the 20 kV/m breakdown values, these simulated storm systems essentially charging to their "Gaussian limit." However, terrestrial dust storms are not as efficient in the charge separation process, usually creating internal fields a few percent of breakdown values. As discussed, other natural systems like volcanic ash

Table 2. Fairweather Current and Electric Field as a Function of Storm Season

	Storm Season	Nonstorm Season	Earth TS
Total J_z, A/m^2	1.3×10^{-9}	4.0×10^{-13}	10^{-12}
Total E_z, V/m	475	0.14	30

and weightless dust in shuttle chambers also tribocharge, but only to a level of a few percent of their respective Gaussian limits. Thus we assume the Martian dust storm is electrically active but assume a more natural situation where the internal tribocharging process is efficient only to at a few percent of the Martian Gaussian/breakdown values.

Given the model we describe above, we find that the current expected from a single small dust storm is ~1 A. This current is driven through the entire fairweather region (of area $\sim 1.5 \times 10^{14}$ m^2), and thus the contribution to the global fairweather current density is $J_z = I/A_{\text{fair}} \sim 8 \times 10^{-15}$ A/m^2 in regions away from the storm. Given an atmospheric resistance at ground level of 3.57×10^{11} Ω-m, the fairweather electric field driven by this single storm is $E_z = \rho_0 J_z \sim 3$ mV/m pointed in the upward direction. By comparison, a small dust devil of 1 km height generates only 2 μA of current and 4 nV/m electric fields, owing to both the smaller generator and increased atmospheric resistance. However, these values are minuscule compared to the current generation from regional storms, which should yield many hundreds of V/m in fairweather regions. The sheer size of these storms, which are many times larger than terrestrial hurricanes, dictates the generation of large currents. We note that the current flow through the upper atmosphere over a regional storm is very large, of the order of 10^5 A. However, this current is distributed over the 500×500 km system, making the current density $\sim 10^{-7}$ A/m^2.

The terrestrial thunderstorm situation is described in the final column of Table 1. A typical terrestrial thunderstorm creates 0.5 A of current. At any time, there are ~2000 active thunderstorms driving a total fairweather electric field of approximately -30 V/m at ground level (the minus sign is indicative of a "downward" electric field) [*Volland*, 1982, 1984].

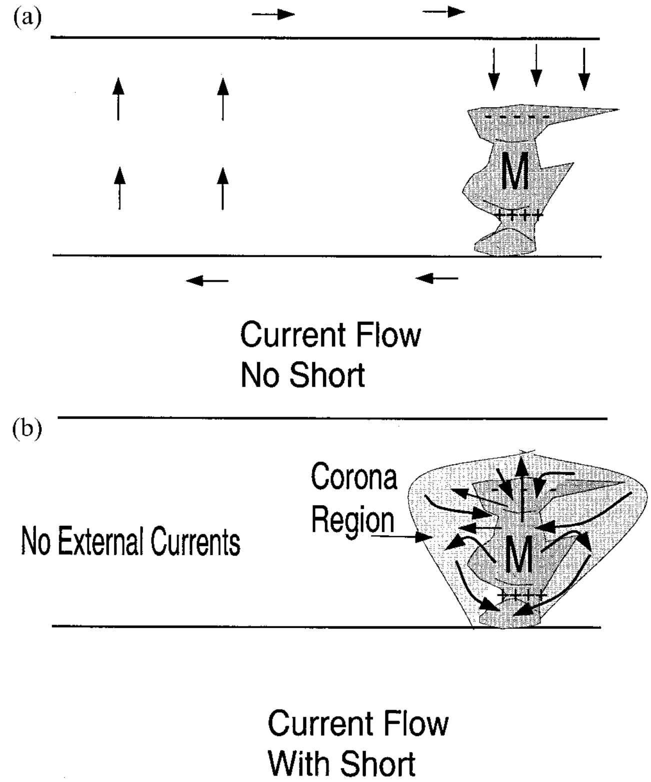

Figure 1. The Martian dust storm (a) without and (b) with catastrophic local breakdown. Note that in the latter case, currents are shorted out locally and do not drive the surface/ionosphere boundaries.

3. Seasonal Currents and Other Considerations

At this time, the exact distribution of dust storms over the planet as a function of Martian year is not fully known. However, there is indication that during dust storm season (northern fall and winter) at least one large regional storm may exist, along with numerous moderate-sized storms [*Gierasch*, 1974]. Given this scenario (see Table 1, row 8), we calculate a collective current in fairweather regions by adding up the contribution from each of the storms in the distribution. This value is presented in Table 2. The collective current (total J_z) during storm season is approximately 1.3×10^{-9} A/m^2. Given such a storm distribution, a corresponding 475 V/m upward directed electric field would be present at ground level in fairweather regions.

In contrast, during quiescent season, dust devils are believed to be the most significant dust-lifting mechanism. These devils occur owing to the static instability of the atmosphere, where hot surface gas rises into the colder atmosphere above. Devils are expected at just about any location, and the Pathfinder meteorological package detected up to 18 vortices (devils or near devils) during its 90 day mission [*Schofield et al.*, 1997]. Consequently, at any given time in the nonstorm season, many thousands of devils are expected on the surface. On the basis of the distribution shown in Table 1, row 9, the anticipated total electric field in fairweather regions is expected to be about +0.14 V/m (see Table 2), much lower than during storm season.

Unlike Earth, there is a large range in expected Martian fairweather electric activity, and the activity has a strong seasonal dependency. We thus anticipate two very different ground-level fairweather electric field values depending on the Martian season, with quiescent values near 0.1 V/m and storm season values near many hundreds of V/m. The factor of 10^3 variation in expected Martian fields is much greater than that for Earth, where fairweather values vary by only a factor of ~2 [*Israel*, 1970, 1973].

As we describe above, we assume that the internal electric fields are a few percent of breakdown values. However, if tribocharging is so efficient that breakdown fields are generated, then a corona may be created surrounding the storm that feeds current inward to negate the dust charge within the storm system [*Farrell et al.*, 1999]. If this process occurs, local coronal currents should "short out" the storm current in its near-vicinity prior to any coupling to the global circuit. Rather than current streams extending far upward and downward from the storm, they are instead localized in the region about the storm. The situation is illustrated in Figure 1. We have assumed that this short circuit process does not occur, but we cannot rule out the possibility at this time, particularly if the tribocharging process is more efficient than assumed.

4. Conclusion

We start with the underlying assumptions that (1) Martian dust clouds have the capacity to create and hold charge (with modest efficiency), (2) the Martian ionosphere is highly conductive, (3) the ground conductivity exceeds 10^{-9} S/m, and (4) atmospheric neutral and charged density profiles are like those

Table 3. A Comparison of the Martian and Terrestrial Global Circuits

	Mars	Earth	Effect
Voltage source	downward-directed dipole moment	Upward-directed dipole moment	reverse current flow between atmospheric circuits
R_H	as low as hundreds of Ωs	78 MΩ	obtain larger currents from Martian storms
R_A	12Ω	250 Ω	more conductive Martian atmosphere
R_G	?	<1 mΩ	if Martian R_G too large, may affect current magnitude and flow
Atmospheric electric field variations	factor of 10^3	factor of 2	Mars fairweather field has a strong seasonal dependency
Atmospheric breakdown voltage	400 V at a few centimeters	30 kV at a few centimeters	lower Martian value may lead to a local "short circuit" effect and destroy global circuit

derived previously [*Cummer and Farrell*, 1999]. Given these assumptions, we present a model that predicts the strength of the fairweather currents and electric fields in regions distant from the Martian dust storms. Our model predicts that these fields can be significant, in the storm season being 0.5 kV/m, and there is a strong seasonal variation, as presented in Table 2. We have discussed several important differences between the terrestrial and predicted Martian atmosphere electric circuits, and these are summarized in Table 3.

The model presented is nonunique in that modification/deletion of any of the assumptions will have a significant impact on the electrification scenario. For example, an upper limit on tribocharging is the development of electric fields near breakdown values of 20 kV/m [*Melnik and Parrot*, 1998; *Farrell et al*., 1999], and the lower limit is the no-charge situation with no internal electric field. The degree of electrification in Martian dust storms is currently unknown; thus we apply a terrestrial analog (i.e., the modest efficiency situation). We leave open the possibility that as more information is obtained regarding Martian dust storms, a more refined model of the electrification process will be available. Even though obvious unknowns remain in the model, the current work is compelling because each of the listed assumptions on its own has a reasonable probability of occurrence. Thus, if dust storms are triboelectric and if the ground conductivity is above $\sim 10^{-9}$ S/m, then a global electric circuit is expected.

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